Chapter 22

Slow Controls

22.1 Overview and general requirements

The $g-2$ experiment is a complex system that involves many subsystems for which adequate sensoring and control during normal operation is required. The purpose of the slow controls and its associated data acquisition system is to set and monitor parameters such as voltages, currents, gas flows, temperatures, etc. These tasks are essential for the successful operation of the experiment over many months of data taking. Immediate online feedback allows the monitoring of the quality of the incoming data and opportunities to react to changes. For example, part-per-thousand gain stability for the silicon photo-multiplier readout of the electron calorimeter is required to meet the systematic uncertainty budget for ω_a. While the gain stability of these photo-detectors will be monitored at the 10^{-3} level or better via a dedicated laser calibration system, immediate feedback on the two parameters (bias voltage and temperature) determining the gain of these devices is achieved via such continuous monitoring. There are many of other cases where such external parameters will be useful in this high precision measurement to establish a full understanding of all systematic uncertainties.

For the setting and read-back of parameters, the slow control system must provide sufficient sensors or control units which will either be directly integrated into the design of new subsystems or come as external devices. Most of these systems will connect to the slow control DAQ via the Midas Slow Control Bus (MSCB [1]) which is a cost-effective field bus developed at the Paul Scherrer Institute (PSI), Switzerland. This very mature system has been successfully employed in other similar experiments and allows for easy integration into the data acquisition framework MIDAS [2]. The slow control DAQ will also include communication interfaces to other external systems like the magnetic and cryogenic controls of the $g-2$ storage ring (iFix [3]) and the Fermilab accelerator (ACNet [4]). Other external devices like the μTCA crates for the readout electronics of the electron calorimeter will be interfaced and monitored.

The demand and read-back values for all parameters controlled by the slow control system will be stored in a PostgreSQL database for easy online access and wherever possible also in the MIDAS data stream for later analysis. While a local copy of the database will be available for online monitoring and analysis, a full copy will be transferred to a Fermilab database server for long-term storage. For efficient use of the read-backs during data taking, user friendly visualization tools will be provided in order to easily access the stored database information. A web browser based framework will be developed to display the large number of different channels monitored by the system.

Preventing unsafe running conditions will require special handling of some critical detector subsystems. Certain sensors will be connected to the experiment's Programmable Logic Controller (PLC) based safety system to provide interlocks and alarms for such situations. For example, the gas flow of the straw tracker will be monitored and shutdown if the flow read-backs are outside normal ranges. This will be the same PLC system used for the main critical experimental systems (like the cryogenic and vacuum controls of the $g-2$ ring) (see section 22.2.4).

22.2 Design

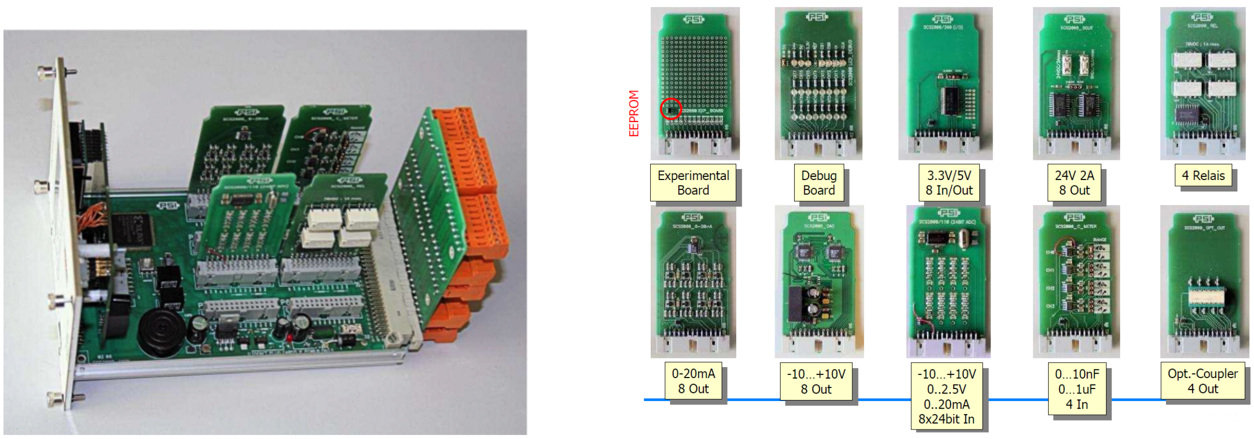
22.2.1 Software and hardware architecture

The slow control system will comprise a variety of sensors and control units described in more detail in the following section. Some of these systems will be purchased as single units (e.g. power supplies) and interfaced via common standard protocols (e.g. RS232, TCP/IP). Other subsystems will be custom-built and their design requires integration of an appropriate slow control interface. The usage of field buses like CAN, Profibus and LON are not justified as their integration requires significant effort. Instead, we will employ the Midas Slow Control Bus (MSCB [1]) which is a field bus developed at PSI. This system was optimized for the environment of a typical physics experiment and for cost-efficiency (typically \$20 per node). In addition, it conveniently integrates into the MIDAS data acquisition system which is the basic design choice for the slow control computing infrastructure.

The MSCB is the default choice for all sensors and control units that are custom built for the $g-2$ experiment. The MSCB is based on the RS485 protocol which is similar to RS232 except for employing differential signals for superior noise immunity. RS485 is a multi-drop, half duplex communication standard so that many nodes can be connected to the same bus but only one can send data at a time. A single submaster can facilitate the communication between the MIDAS host computer and up to 256 individual MSCB nodes. In fact, by employing a layer of repeaters, up to 65,536 nodes can be operated on a single bus with up to a few km long cables. The MSCB requires two signal wires for the differential signal and a ground wire. Three additional lines provide power ($+5\,\mathrm{V}$, $\pm 12\,\mathrm{V}$). The usage of a 10-wire flat ribbon cable provides four additional digital lines for application specific usage.

The MSCB protocol is byte oriented and uses bit 9 from RS232 for addressing purposes. As this bit usually cannot be switched on and off quickly enough in the UART (universal asynchronous receiver/transmitter) of a PC, simply using RS232-RS485 converters is not sufficient. This can be overcome by employing a submaster on the computer side with a micro-controller to provide the handshake with the PC and enough memory to avoid data loss. In this scheme, bit rates of up to 42 kB/s are sustainable.

The development of the MSCB hardware at PSI had several iterations with increasingly sophisticated units. The latest generation is a general purpose unit, SCS2000, as shown in Fig. 22.1(a) and is successfully employed in the MEG experiment at PSI. The SCS2000 unit has an on-board programmable logic device (CLPD, Xilinx XC2C384) which communicates with the submaster via the MSCB on one side. On the other end, there are slots for 8 independent MSCB daughter cards which are each accessed by the CLPD via a 2-lane SPI and a parallel 8-bit bus. The available daughter cards come with a multitude of different functionality. Examples are shown in Fig. 22.1(b) and the complete set of these daughter cards comprises functions like digital I/O channels, 24-bit ADCs, DACs, current sources, valve controls, and many more. Each SCS2000 unit can carry daughter cards of different functionality so that we will be able to fill up each unit to meet the various applications for $g-2$. Because the MSCB protocol and communication is handled by the central programmable logic device in the SCS2000, the daughter cards only require a simple design and the whole package offers a relatively cost-efficient solution.



(a) (b)

Figure 22.1: a) SCS-2000 general purpose control unit. b) Examples of available SCS200 daughter cards.

As mentioned before, the MIDAS software framework will be used for the slow control data acquisition. Straightforward integration of MSCB-based hardware is already provided by appropriate drivers integrated into the software package. The end user has to provide an application specific frontend module to control the specific sensor or control unit, i.e. to set and readout parameters of the hardware system. Setting of the parameters such as detector voltages, amplifier gains for the SiPM readout of the calorimeter or the readout rates of sensors are handled by corresponding settings in the online database (ODB) on the slow control computer. Some of these values will be set based on the readback and subsequent online analysis of slow control parameters. A backend main server will handle the collection of the readout data with an adapted event builder provided in the MIDAS software. The assembled MIDAS events from all slow control subsystems are then handed off to a data logger module which will store the data in the MIDAS output stream and a PostgreSQL database locally as well as transfer it to the Fermilab long-term storage server.

Figure 22.2 summarizes the general components of the slow control system indicated by the solid colored boxes. A single slow control backend host (brown box) manages the communication with all MSCB nodes (blue boxes) via the MSCB submaster (green box). Non-MSCB based sensor and control nodes (purple boxes) will communicate directly with

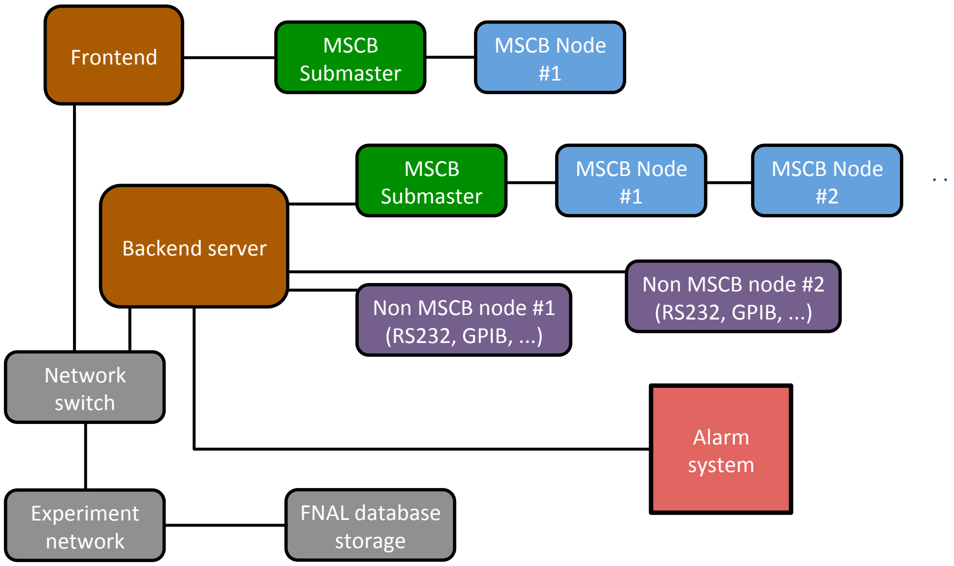


Figure 22.2: Slow control system for the $g-2$ experiment: The basic layout includes a backend host (brown box) which manages the communication with all MSCB nodes (blue boxes) via the MSCB submaster (green box). Non-MSCB nodes (purple boxes) directly connect to the backend via the appropriate interface (USB, serial port, ethernet, ...). Additinal frontend computer(s) with their own MSCB bus and nodes for dedicated applications communicate and exchange data with the backend server via the Ethernet network. The stand-alone alarm system (red box) will provide adequate measures to prevent unsafe running conditions.

the backend server via appropriate interfaces (e.g. USB, serial port, ethernet, ...). During the development phase of the $g-2$ experiment, we expect several institutions to set up their own MIDAS and MSCB host computers for testing of individual components (e.g. the MSCB interface for the SiPM bias voltage control). Although a single main PC and submaster are sufficient to handle all MSCB nodes in the $g-2$ experiment, these additional available host computers with their MSCB submaster and nodes can be easily integrated into the slow control system. Therefore, the final implementation in E989 will involve additional MSCB frontend hosts to control special subsystems. Data exchange between a frontend computer and the slow control backend computer happens via ethernet network. This scheme adds redundancy to the system in case of maintenance or failure of one of the computers since MSCB nodes and their appropriate MIDAS software frontend can be easily ported. The system is completed by the stand-alone alarm system (red box) to provide appropriate actions in case of unsafe operating conditions of various detector subsystems.

In the following subsections, we will describe the sensors and control units, their requirements and the institutional responsibility. Thereafter, the design of the alarm system, the backend server and the data storage are provided.

22.2.2 Sensors and controls

The $g-2$ experiment will employ a variety of systems to facilitate the overall measurement of the muon anomalous magnetic moment. Figure 22.3 displays the current required functionality with respect to the slow control measurements broken down by various subsystems. The corresponding Table 22.1 lists the actual parameters set and monitored via the slow control data acquisition and the institutional responsibility for each component. The read-back precision are best estimates and are subject to change.

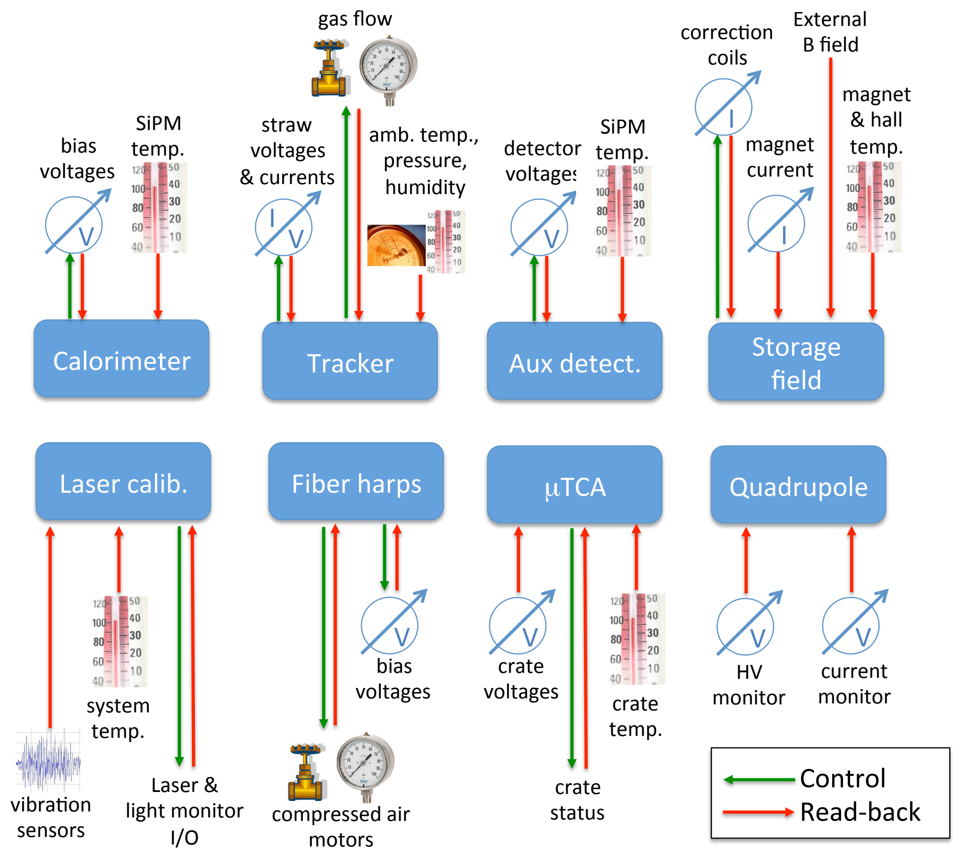


Figure 22.3: Schematic breakdown of the individual slow control nodes showing the controlled parameters and sensor read-backs.

The photo-readout of the electron calorimeter will be based on silicon photo-multipliers (see section 17). The design incorporates a surface mount SiPM on a readout board integrating the bias voltage supply and an amplification of the readout signal with adjustable gain. Since the experiment requires part-per-thousand gain stability, a stabilization and monitoring of the two external parameters that determine the SiPM gain, namely the bias voltage and temperature, is required. The bias voltage of each of the 1296 SiPM channels is set and monitored for each channel and the temperature sensors will be placed on each of the amplifier boards. Compensation of changes in the gain of each channel will be performed by adjustments to the variable gain setting of the differential amplifier stage.

The associated laser calibration system for the calorimeter allows us to monitor absolute gain changes in each calorimeter channel. For that purpose, we will need to monitor the laser intensity and the temperature of the light distribution system at several locations. The total number of channels required for the laser system is expected to be less than 100.

The tracker system comprises three stations of straws located inside the scallop regions of the vacuum chambers. The slow control will provide readings for ambient temperature, humidity, and pressure at those three locations. It will also monitor the gas flow and temperature as well as currents and voltages for both the straw high voltage and the electronics low voltage systems of each of the eight modules per station. The slow control will provide the mechanism to set the high voltage demand values in addition to the read-back of the actual values. The experiment's PLC safety system (see section 22.2.4) will provide interlocks for immediate shutdown of gas and HV in case of irregular running conditions.

Table 22.1: List of control and read-back parameters in the $g-2$ experiment handled by the slow control unit with anticipated read-back precision and rates, channel counts and the institutional responsibility for the implementation of the actual devices.

Parameter	**Read-back precision**	**Channel count**	**Responsibility**
Calorimeter			
SiPM bias voltage	$\sim$mV	1300	UVa, JMU
SiPM amplifier gain		1300	UW
SiPM temperature	0.1° C	1300	UW
Laser calibration			
Laser temperature	$< 0.5\,^\circ$C	< 10	INFN, NIU
Output signals (enable)		< 48	INFN
Input signals		< 48	INFN
Serial laser interface	–	< 10	INFN
Tracker			
HV voltage	~ 1 V	54	FNAL
HV current	$0.1\,\mu$A	54	FNAL
HV status	–	54	FNAL
LV voltage	~ 0.1 V	54	UCL
LV current	$\sim 10\,\mu$A	54	UCL
Electronics temperature	~ 0.5 C$^\circ$	348	FNAL, BU
Cooling temperature	~ 1 C$^\circ$	54	FNAL, NIU
Amb. pressure	few mbar	3	NIU
Amb. temperature	$< 0.5\,^\circ$C	3	NIU
Amb. humidity	few %	3	NIU
Gas flow		48	FNAL, NIU
Electric quadrupole			
Voltage (0-10 V)	0.1 V	5	BNL
Current (0-10 V)	0.1 V	5	BNL
HV disable / enable	–	5	BNL
Aux. detector: Fiber harps			

Table 22.1 – *Continued from previous page*

Parameter	**Read-back precision**	**Channel count**	**Responsibility**
SiPM bias voltage	few mV	2	Regis
SiPM temperature	0.1° C	4	Regis
Motor control	-	4	Regis
Aux. detector: Entrance counter			
SiPM bias voltage	few mV	2	Regis
Field			
Main magnet current		1	FNAL
Surface coil current		200	FNAL
Yoke temperature	$< 0.5\,°$C	~ 60	NIU
Hall temperature	$< 0.5\,°$C	~ 5	NIU

The quadrupoles are supplied by five power supplies which each have two low voltage (0-10 V) outputs for monitoring of the actual high voltage and the current, respectively. The slow control will incorporate 2 ADC daughter cards (±10 V range) for the SCS2000 units that will accomodate the 10 channels of this low voltage measurements. A remote HV enable (2.5–15 V) / disable (0-1.5 V) signal for each unit is handled by one 8 channel digital output card for the SCS2000 unit. The quadrupole power supplies will also be fast interlocked (potential free switch) by the PLC alarm system in case of bad vacuum, a storage ring magnet quench, or X-ray detection during access to the main experimental hall during operation.

The fiber harp detectors will be equipped with SiPMs as the photo-sensitive detectors. Their bias voltage power will be supplied through two additional channels of the calorimeter bias supply system. As the SiPMs for the readout of the fibers are grouped in 4 rows of 7, we anticipate monitoring the SiPM temperatures with one probe per row. As the fiber harps are rotated into the beam by compressed air actuators, 2 control channels and read-backs must be available. These are controlled by an Arduino board which will have an MSCB interface.

Beside the fiber harp, the auxiliary detectors also include the so-called t_0 entrance counter which is a Lucite Cerenkov sheet readout by two SiPMs. It requires two channels for the control and read-back of the bias voltage. If required, temperature monitoring can be added.

The communication between the slow control DAQ and the μTCA crates will be done via software (see Section 22.2.3). The μTCA crates already have an integrated on-shelf manager that can read the status of parameters provided by the crate such as voltages or temperature.

The field measurement in Fig. 22.3 includes readouts of the correction coil currents. It is most likely that these are directly interfaced by the DAQ for the fixed NMR probes. Current read-backs of the main storage ring magnet and other beamline magnets will not be directly interfaced by the slow control DAQ but the data will be received via software interfaces. The slow control will incorporate temperature sensors placed onto the magnet steel around the ring and hall temperature monitors. Since changes in the magnet temperature are the main driver for changes in the field homogeneity, monitoring will allow for detection of any irregular temperature trends which could be caused by a deterioration of the magnet insulation. Overall, we expect a total of <100 temperature probes for the entire experiment (mainly for the magnet steel) with a read-back precision of at most 0.1° C. Since we are mostly sensitive to temperature changes, the absolute accuracy is of less importance. For the implementation of these temperature sensors, we will use the above mentioned general purpose SCS2000 unit with existing 8-channel temperature daughter cards based on the Analog Device AD590 2-terminal temperature transducer. Since each channel senses the current in the AD590, long cables of more than 10 m can be used so that the SCS2000 unit(s) may be located at the center of the ring.

22.2.3 Communication with external systems

The slow control DAQ will not only retrieve data from the various sensors described above but also communicate with other systems in the $g-2$ experiment and the Fermilab accelerator infrastructure. As of now, there are a total of three such systems. Communication will need to be established with the main ring control system, the Fermilab accelerator complex, and the μTCA crates used for the readout of the electron calorimeter stations.

The ring control system for the cryogenics and vacuum is based on PLC interfaces which are accessed via the human machine interface iFix. The communication path (thick double arrow) between the iFix server and the slow control DAQ system will be facilitated via an Object Linking and Embedding for Process Control (OPC) server integrated into iFix. The communication on the slow control DAQ side is handled by an OPC client which is available as commercial or open-source products for the Linux based system. Alternatively, the OPC server might directly write into the PostgreSQL database.

During the $g-2$ operation, some parameters of the accelerator (like magnet currents, beam intensities, status of other beam elements) will be stored in the output datastream. This information can be retrieved via a data broker from the accelerator network (ACNet). Retrieval of accelerator related parameters is already implemented at Fermilab in the larger context of a beam database for the intensity frontier experiments (IFbeam) and we will be able to benefit from this existing implementation by adapting it to our needs and software infrastructure. The data is usually stored in PostgreSQL format and can be integrated into our experimental condition database.

A third system that we want to establish communication with is the μTCA crates for the readout of the electron calorimeters and possibly other electronics in the experiment. These crates typically provide internal status parameters (e.g. temperature, fan speeds, error indicators etc.) that are useful to monitor to quickly identify hardware problems or failures. System management and monitoring is achieved by means of software solutions based on the Intelligent Platform Management Interface (IPMI), a standardized computer system interface. An IPMI system manager connected to an application programming interface (API) over TCP sockets has been developed for the μTCA crates employed in the CMS experiment. We will adapt this software development for $g-2$ as it provides the functionality of monitoring various crate parameters.

22.2.4 Alarm system

While the slow control DAQ provides means to ramp down high voltages or close a valve, the availability of an additional fast hardware interrupt is preferable for the case of unsafe running conditions. An alarm system will serve the purpose of allowing quick and safe shutdown of certain elements of the $g-2$ detectors. This will be part of the PLC-based system handling the more critical components like the cryogens of the magnet as well as vacuum controls. There is plenty of capacity present within this PLC system and, if necessary, this alarm system can be implemented as a separate sub-master connected to the main system. The system described here will deal with detector components which are not critical in the sense of life threatening unsafe conditions. The interrupts provided by the slow control alarm system are mainly for protection of the detector components and electronics.

At this moment, we plan to provide hardware interlocks for the high voltages and the non-flammable gas for the straw detectors which are located inside the vacuum. Scenarios necessitating shutdown of voltages and gas flow could be vacuum leaks in the ring vacuum chambers, overheating or high fluctuations in the straw current that could indicate a developing problem. The quadrupole power supplies will also be connected to the system and interlocked in case of bad vacuum, a magnet quench or X-rays from sparking plates during person access to the $g-2$ hall. An interlock for the laser calibration system might be useful to protect the system in case of overheating or abnormal parameters. Similarly, hardware interlocks for the SiPM bias voltages could be provided in the same scheme if the request for it arises.

The PLC sits at the center of the system as shown in the schematic layout in Figure 22.4. Various input levels from other systems such as a good vacuum indicator or ring magnet status feed into the PLC. Those input levels are then used in the program running inside the PLC to determine the appropriate output levels of the interlocks for the various detectors. Our design also includes additional switches on the input level side as a measure to allow for bypassing of certain alarm channels. This can be very helpful during detector testing, maintenance or debugging where it is desirable to disable a specific input or output channel without interfering with all others. As the PLC is programmable, a hardcoded timeout interval could be added to automatically switch back on the bypassed channel.

The output channels of the PLC are then fed into the interlock channels of the detector electronics to shutdown high voltages, close gas valves or switch off other components. Additional alarm horns and sirens will be triggered for interlocks that require immediate intervention by shift personnel. A logical OR of all channels will be fed onto pin 10 of the parallel port of into the slow control computer where it can generate an interrupt to trigger software alarms and phone calls to appropriate system experts or the control room. Interpretation of the cause of the specific alarm happens by feeding an additional copy of each output channel onto the data pins of the parallel port card. A similar scheme of parallel port interrupts was already successfully applied in the test beams for the calorimeter and straw tracker and was used to monitor signals of the arriving beam to the DAQ. The adaption of the developed kernel drivers for the alarm system is therefore relatively easy.

22.2.5 Backend server

The backend server is the central computer in the slow control DAQ to communicate with the various control units and sensors and retrieve all read-backs. Since data rates on the slow control backend server are low (less than 1 MB/s), a standard modern Linux desktop is sufficient. It will be equipped with enough interfaces (RS232, USB, MSCB) for the external devices. As mentioned above, we will work within the MIDAS software framework to coordinate the different tasks. The various sensors and controls can be accessed individually by independent frontend programs which run in parallel within the main MIDAS server. Each frontend has its specific functionality to set experimental parameters (like high voltages for each SiPM), read-back parameters, and to change read-back rates. Some hardware parameters might be set depending on the outcome of certain analyses routines. These analysis frontends can also be run on the backend server since MIDAS already provides for a convenient framework of an online analyzer.

For MSCB devices, necessary hardware drivers are provided by MIDAS so that the actual implementation of the interfacing software frontend is simplified. For other hardware connecting to the backend over RS232 or USB, MIDAS also includes software components that will make integration of these subsystems into the slow control easier. Such frontend code has been developed previously for experiments like MuLan [5] and MuCap [6] at PSI by some of the current E989 collaborators. Therefore, the implementation of the various frontends for all sensors and controls will not pose a major effort.

22.2.6 Data storage and access tools

For the data storage of slow control parameters, we will use a PostgreSQL databases. While MIDAS has already built in options for MySQL handling, Fermilab's preferred choice is PostgreSQL and so is the current anticipated choice for E989. Integration of PostgreSQL capabilities should be feasible with minimal effort and we have started adapting the appropriate parts of MIDAS. The backend server will have standard ethernet network connection(s) for the communication with external systems (see section 22.2.3) and synchronization of the local database with the remote long term storage at Fermilab. We will employ the automated script-based mechanisms developed at Fermilab for this purpose. Overall, the database handling and storage is expected to nicely integrate into the existing infrastructure.

From Table 22.1 one can deduce that the anticipated maximal channel count for the slow control is about 3000 readout channels with expected rates of $\sim 1\,\mathrm{s}^{-1}$. If we recorded for every single channel three float values (4 bytes) in form of a timestamp, demand, and current read-back value, we therefore can deduce a conservative upper limit of the expected data rate of 32 kB/s or 3 GB per day. Given the standard storage sizes of more than 1 TB today, the overall slow control data for the entire $g-2$ data taking period will be easily storable and does not pose any major challenge.

Any data acquisition requires a well-designed user interface for online monitoring and the offline analysis. For example, a user friendly visualization interface to inspect the large number of different channels (the calorimeter alone has 1300 channels) is essential during data taking. Based on past developments for muon precision experiments at PSI and other current Intensity Frontier experiments at Fermilab, we will have a variety of options to establish such tools. The IFbeam software tools incorporate the python based Web Server Gateway Interface and subsequent Google Charts to access and display database information in the web browser. The experiments at PSI, MuLan and MuCap, used custom developed web browser based tools to query and display the database information as well as standalone graphics displays within the ROOT framework [7]. The ROME software framework is well integrated into the MIDAS data acquisition framework and can be used for online monitoring of slow controls and other data [8]. At this point, we have started to collect software requirements across the entire experiment to coordinate and efficiently develop such tools that fit most of these applications. In general, usage of a single tool will increase user friendliness but it could be advantageous to have optimized tools for various different data streams. In any case, the specific implementation will profit from extensive former experience which will guide the collaboration in making the final decisions in the future.

22.3 Alternative Design Considerations

The information recorded by the slow digitization DAQ is quite independent from any other DAQ system in the $g-2$ experiment. Therefore, we have investigated the usage of alternative software packages like the ORCA system. The collaboration has used this system in the ongoing SiPM tests at UW in order to gain practical experience with this system. Another option is the EPICS software which is well supported at the Advanced Photon Source at ANL and at FNAL. However a careful comparison of the three systems has revealed that MIDAS is our best choice for the software framework for the slow control DAQ. Its major advantages are the fact that several of the $g-2$ collaborators have many years of experience with this system. It has been used successfully by a variety of experiments at PSI and other laboratories. We also have a good relationship with the main developers of MIDAS at PSI. Last but not least, synergies with the fast detector DAQ are obvious as it is based on the same framework. The amount of maintenance and debugging reduces and collaborators on shifts will only need to familiarize themselves with the subtleties of one system.

The default choice of the MSCB for hardware components is tightly connected to the decision for using the MIDAS framework as the latter has easy integration of MSCB components. In addition, the MSCB is optimized for cost efficiency. We have looked into the usage of more commercial products (e.g. National Instruments hardware with possible integration into LabVIEW) but such systems would simply increase the cost. In addition, some of our systems require custom built components (e.g. the extremely stable low voltage power supply for the SiPM) and therefore, we can profit from the simplicity of the MSCB protocol. Finally, the MIDAS and MSCB framework is very open and we have good connections to one of the experts of this system at the Paul Scherrer Institute, Switzerland. We are therefore confident, that development of new modules should be feasible with limited effort. It should also be noted, that we can still rely on non-MSCB off-the-shelf components if it turns out that they are an optimal choice to control or monitor some of our subsystems. Communication with such devices via typical standards of RS232 or USB is available within the MIDAS framework. Our default choice is therefore very modular and expandable but comes at a quite optimal cost.

22.4 ES&H

The slow control system will involve sensor and control units that mainly need low voltages and currents for operations. If high voltages (like for the SiPM bias voltage or the PMT voltage) are involved, adequate protection (shielded cables, enclosed and fused electronic components) will be employed to comply with Fermilab's safety rules. All SCS2000 units purchased from PSI come with a full enclosure and meet standard electrical safety requirements. The components for the slow control do not require any hazardous materials and there are no mechanical hazards since the components are typically small.

The alarm system included in the design of the slow control will interlock non-critical components to prevent direct damage to the hardware. It does not include any life-threating hazards.

22.5 Risks

The default design of slow control relies on the mature MSCB system that has been successfully employed in several experiments. Therefore, there is only a small risk that components will not work appropriately to the specified requirements. Sensors (like temperature, voltage, currents etc.) are readily available and there are no real indication that they would not meet the requirements in the E989 experiment. In the unlikely event that we cannot meet the requirements, a design of an appropriate component would require additional resources. Since the design of a new MSCB node is not too complex, the associated cost risk is rather small.

A failure in meeting the specified requirements for controlling devices and read back of performance parameters potentially causes an inability of detecting a loss in the data quality during the experiment. This could result in the necessity of dismissing data from the analysis and could result in the need of longer data taking to acquire the full statistics.

Any components installed close to the precision magnetic field (especially electronics circuits with time-varying currents) can cause a static or dynamic distortion to the homogeneity of the field and possibly decrease the precision in its measurement. Mitigation of this risk is achieved by using non-magnetic materials close to the field region and by testing all components for their magnetic properties in a 1.45 T test magnet and with specially designed pickup coils for transient fields.

22.6 Quality Assurance

The implementation of the slow control system relies on well established software in the form of the MIDAS framework. In addition, we will employ the very matured MSCB hardware whenever possible or purchase commercially available systems. Quality assurance measures are therefore mainly limited to verifying that custom-built sensors and control units meet the requirements that all systems work properly and comply with all safety regulations. We will extensively test individual components and the full system in dedicated bench tests before the final installation in the experimental hall. As outlined in the risks, these tests will include the verification of the stringent magnetic requirements for components installed in the vicinity of the precision magnetic field of the storage ring. In addition, several institutions across the collaboration will have their own small slow control system to develop individual components. This will help identifying any problems and debugging the system's functionality. At Argonne, we have already successfully tested one SCS2000 together with temperature and ADC readout cards. These tests have verified the easy integration and handling of those units within the MIDAS framework.

Since the slow control provides an online monitoring of the status of many systems in the $g-2$ experiment, care will be taken to properly design the appropriate visualization tools providing easy access to all parameters. This will be an important component in detecting any changes in the quality of the collected data during the experiment.

22.7 Value Management

The usage of the freely available open-source MIDAS software and the specifically cost-optimized MSCB hardware is key in keeping the slow control systems overall cost low. Some components that cannot be readily purchased (like the SiPM bias voltage supply with its stringent requirements, see section 17.4.2) need to be custom-built. Most of these will be designed and implemented by collaborators at universities and outside the US in order to keep the overall cost low. At the same time, the centralized integration of all components at Argonne will allow verification of the full system and detection of any interference of different sensors or control units.

22.8 R&D

Necessary R&D for cutom-built components that will be integrated in the slow control system is performed by some of the collaborating institutions and will be described in the appropriate sections in this document. Examples for these are the SiPM bias voltage supply (section 17.4.2) or the laser calibration system (section 17.4.3).

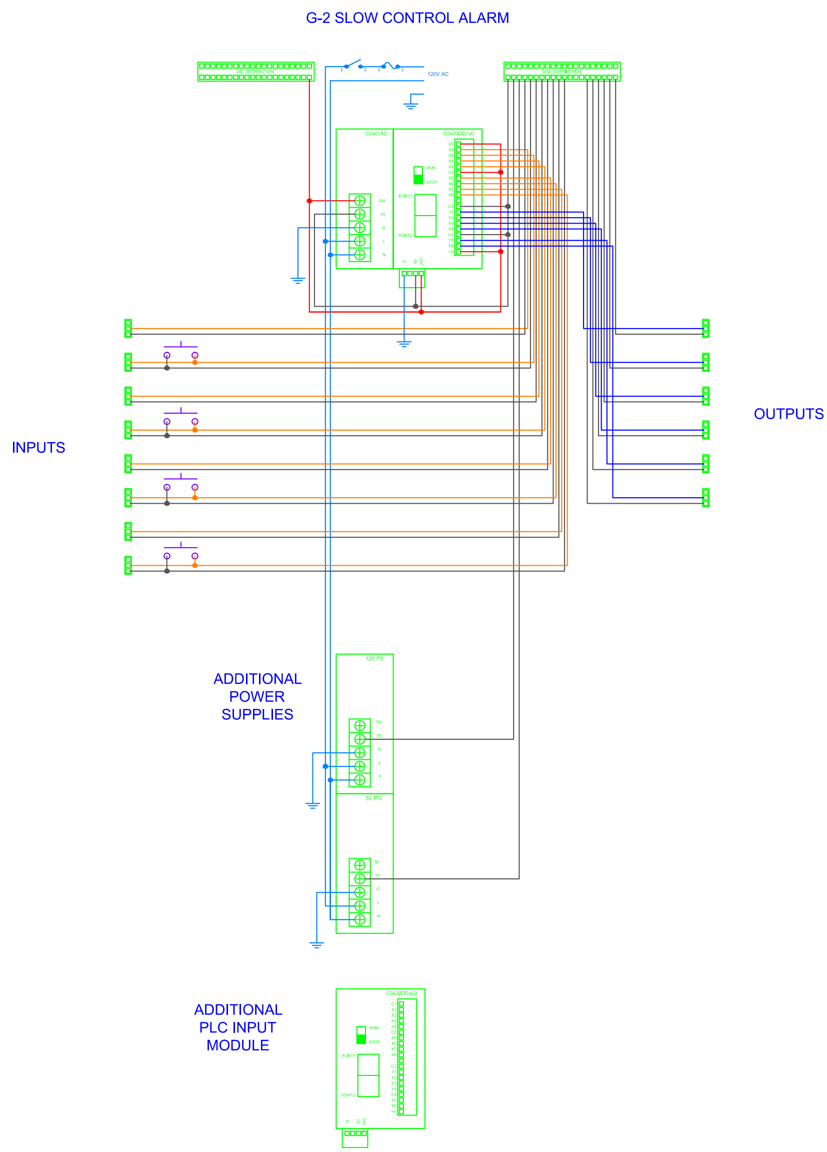


Figure 22.4: Layout for the stand-alone slow control alarm system based on a CLICK PLC.

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